Overview of Techniques for Mitigation of Fading and Shadowing in the Direct Broadcast Satellite Radio Environment

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Abstract - **The DBS radio propagation environment is divided iato three still-cllvir()lllilc]lls, indoor, rural-suburban mobile and urban mobile. Indoor propagation effects arc in a large part determined by construction material. Non-metallic materials afford direct, albeit attenuated, penetration of the satellite signal with a minimum of multipath signal scattering. Signal penetration into structures using significant metallic materials is often indirect, through openings sock as doors and windows and propagation will involve significant multipath components. Even so, delay spread ia many situations is oa the order of 10's of nanoseconds resulting io relatively flat fading. Thus frequency diversity techniques such as Orthogonal Frequency Division Multiplex (OFDM) and Code Division Multiple Access (CDMA) or equalization techniques do not realize their intended pert'ormolwc enhancement. Antenna diversity, directivity and placement arc key mitigation techniques for the indoor environment. In the Rural-Suburban mobile environment with elevation angles greater than 20", multipath components from the satellite signal arc 15-20 dB below the line-of-sight signal level and often originate from nearby reflectors. Thus shadowing is the dominant signal impairment and fading effects arc again found to be relatively flat for a large fading margin. Because receiver motion induces rapid variations ia the signal level, temporal diversity techniques sock as interleaving, channel coding and retransmission can be used to combat short intermittent fading events. Antenna diversity and directivity techniques are again useful in this environment. Finally, in the Urban mobile environment, slower vehicle speeds and blockage by buildings causes signal fades that arc too long and too deep to combat with signal margin or time diversity. Land-based signal boosters arc needed 10 fill in the coverage gaps of the satellite only broadcast scheme. On frequency boosters arc suggested 10 conserve bandwidth yet these produce long delay multipath and create a frequency selective fading environment. Enter now OFDM, spread spectrum, equalization and other techniques that are capable of deconvolving the channel effects and effecting significant performance improvements by extracting the frequency diversity or time diversity components comprising the received signal.**

Introduction

Mobile radio propagation at L- and S-bands is hampered by signal shadowing and multipath from natural and man-made structures. The understanding of these effects and their mitigation arc the subjects of many technical articles and books. A subset of these investigations arc either applicable to or directly address Land Mobile Satellite Service (LMSS) configurations. Wc can further subdivide these into three propagation environments, indoor, rural-suburban mobile and urban mobile. Any Direct Broadcast Satellite - Radio, DBS-Radio, system design is based in large part on a thorough understanding of the propagation impairments and mitigation techniques associated with these environments.

The three following sections address these three environments. In each section wc review important results from applicable UHF, L-band and S-band propagation measurements and discuss techniques to mitigate the LMSS signal impairments. In the sections covering indoor and rural-suburban mobile propagation, Satellite-only broadcast is assumed. In the ot-bm-mobile section, it is noted from the outset that severe satellite signal shadowing requires some form of gap-filling technology. On frequency repeaters arc suggested for reasons of bandwidth efficiency and discussion switches to a joint satellite ground transmission scheme and the associated propagation effects and mitigation.

Propagation for indoor Portable Reception

One of the common environments for DBS-Radio will be the indoor home or business environment and listeners will expect adequate reception using only the antenna built into the receiver. Understanding the satellite to indoor propagation mechanisms is therefore of prime importance to the DBS-Radio system designer. In this regard there are ninny experimental results in the literature describing the propagation impairments associated with building penetration and indoor propagation at UHF, L-band and S-band frequencies. Table 1 summarizes some of these results that apply to DBS Radio.

Spatial Variations

As expected, building structure and construction materials have a large impact cm propagation effects. Non-metallic construction homes exhibit the lowest mean signal attenuation, 5-11 dB, with a standard deviation of 2-3 dB as the receiver is moved around inside the building, [2][3]. Signals penetrating office structures with some metallic construction materials experience larger mean signal losses of 5-14 dB. Reduction of the direct signal and increased multipath from the metallic materials raises the received signal standard deviation to 3-10 dB, [3][4][6]. An analysis of the spatial variations inside two office structures [6] showed close agreement with a Rician distribution having random/specular power ratio, K = -6.8 dB for one building and K= -11 dB for another. The spatial signal variations measured showed a quasi-periodic structure with trough-to-trough distances of 2-4 wavelengths for the satellite transmissions and 0.5 to 1.5 wavelengths for the low elevation angle transmissions. The reasons for this difference were not concluded.

Spectral Properties

ATS satellite tests [4] of signal penetration into single family non-metallic construction dwellings Showed mean attenuation increasing by 2-3 dB per frequency octave over the range of 0.9 to

2.6 GHz. In particular they measured mean signal losses of 4.6 dB, 6.7 dB and 7.5 dB for 860, 1550 and 2569 MHz frequencies respectively. This same characteristic was corroborated by measurements reported in [3]. The opposite trend was observed for office buildings and semi to heavily metallic structures. Attenuation in these structures was observed to decrease by 2-5 dB per frequency octave, [3][7][8][9].

The following explanation seems reasonable. For the non-metallic structures, the primary signal penctt-alien and propagation paths are through walls and ceilings. This mode favors lower frequencies. in the case of office buildings and other structures using metallic construction materials, the primary signal penetration and propagation paths are through openings such as windows, doors, etc. This mode favors higher frequencies.

Temporal Signal Variations

Even with the transmitter and receiver locations fixed, the signal level at the receiver can vary significantly according to changes in the environment that affect propagation paths. Low elevation angle, ≈ 0°, experiments showed indoor temporal signal fading that was Rayleigh or Rician distributed with a dynamic range of 17-30 dB [6]. These variations resulted from the movement of outdoor traffic or people and doors inside the building which changed propagation geometries. In higher elevation satellite experiments [3] people moving near the receiver produced less than 0,5 dB signal variation. Presumably the higher elevation angle signal and its reflections encountered fewer moving objects in their path to the receiver, thus there was little to no change in the propagation paths. The exception to this was when a person blocked the direct transmission path, resulting in signal attenuation of 6-12 dB.

Elevation Angle Properties

Signal loss measurements made in [3] and [4] showed no dependence on elevation angles ranging from 12° to 55° for structures not blocked by external objects. Two different explanations accompany this result. First, for non-metallic structures where signal penetration is primarily though walls and ceilings, a signal arriving al an elevation angle greater than 100 will not encounter many movable obstacles and thus the signal variations were fairly similar over the test range of 12° to 55°. Second, for metallic structures were signal penetration is primarily through openings, the elevation angle of the direct signal has little 10 no impact on the entrance of the signal into the building and thus we would expect no dependence on elevation angle.

Delay Spread

In the articles that were reviewed, measured delay spread varied over a range of 10 ns to 350 ns. This corresponds to a coherence bandwidth range of 0,5 to 17 MHz. Thus we can say for most single channel per carrier DBS-Radio broadcast schemes, the indoor fading, channel wi II look flat across the band.

Difficult Situations

There are many structures and situations were there is significant excess path loss. These include family dwellings and non-residential buildings using significant metallic construction including aluminum siding, corrugated steel, wire mesh screens, aluminum backed sheet rock, etc. The construction materials used in these buildings inhibits signal penetration through walls and entrance of the signal through openings such as doors, windows, etc. becomes the primary mode. The average path loss in these cases can be 10 to 20 dB more than the nominal 5 to 11 dB observed in structures making less extensive use of metallic construction materials.

Structures shadowed by trees, mountains or other buildings will experience excess loss if the obstruction blocks the satellite line-of-sight. During 1,6 GHz measurements on residential structures in Houston, TX [4] excess signal blockage from trees was measured at 12-15 dB. These blockage situations would increase in number and likely intensity as elevation angle decreases.

Signal Fading Mitigation for the Indoor Environment

Ten to fifteen dB fade margin will mitigate direct path signal attenuation in structures that make partial or no use of metallic construction materials. Additional techniques are needed for deep fades in bad locations or in difficult buildings making extensive use of metallic materials.

The spatial null separation measured in [3] and [6] suggests that a diversity antenna separation of I wavelength could put one antenna out of a null zone. Difficult structures may require the placement of an antenna external to the structure.

An alternative to antenna diversity is to use antenna element combining or switching to achieve signal directivity/nulling and thus reduce multipath fading,

The simplest mitigation technique is the listener's effort to place the radio m its antenna in a good signal location. This approach may be somewhat hampered by the proximity effect of the listener's body.

Spread spectrum, COFDM and equalization techniques can help in the office building environment w'here coherence bandwidth is smaller and standing wave signal levels had a measured standard deviation of 3-10 dB. These techniques will be less effective in residential structures where delay spread can be less than 10-20 ns. More discussion is given to these schemes later in this paper.

Propagation for the Rural and Suburban Satdlitc-Mobile Environment.

A significant body of measurement results and theoretical modeling exists on the LMSS channel. As part of this, important LMSS propagation tests were accomplished in the United States by Hess [11] and Goldhirsh, Vogel, et. al.[see Table 1.1 of Ref. 17 for list of 11 publications], in Canada by Butterworth [12][13], in Europe by Jongejans et al., [14], and Renduchintala et al., [15] and in Australia by Bundrock [16]. These tests included ATS-6, MARECS, INMARSAT, and ETS satellites as well as simulations of the LMSS channel using balloons, towers and aircraft. Results from these sources were distilled by Goldhirsh and Vogel in NASA Reference publication 1274, "Propagation Effects for Land Mobile Satellite Systems: Overview of Experimental and Modeling Results" and released in February 1992 [17]. The results of these and related studies are further distilled and summarized in table 2.

The coarse structure of the LMSS signal fading is dominated by the intermittent blockage of the line-of-sigi~[by roadside objects such as building and trees. In the rural and suburban environment tree shadowing is the predominant LMSS signal impairment. In most situations in the Continental United States (CONUS) the elevation angle to a direct broadcast satellite would be above 20° with the result that the attenuation path is limited to 1 or 2 tree canopies. The mobile antenna is often directive in elevation, discriminating low elevation signal scattering and multipath reflections from the ground. Thus signal absorption, scattering and re-radiation by the canopies of 1 or 2 nearby trees gives rise 10 the major attenuation components. Although omni-directional antennas are more susceptible to low angle multipath from surrounding signal scatters, it was found through measurements and modeling that even with these less directive antenn as, the primary fading effects arise from the shadowing of the line-of-sight signal component.

Vogel and Torrence [18] simultaneously measured signal attenuation at 1600" and 2500 MHz of various tree types. Their results showed average fades of 4 - 9 dB with no measured dependence of fade level on frequency. Multipath components appeared at a level 15-20 dB below the unattenuated line-of-sight signal and thus the shadowed line-of-sight signal dominated the propagation statistics recorded. Results summarized in the NASA publication [17] showed similar fade levels with some tendency of increased signal impairment for increasing frequency. Of particular interest is the finding that signal absorption and scattering from branches is the main attenuation mode as opposed to the effects of leafy foliage. Goldhirsh and Vogel quantified the effect of full foliage as an increase of 35% in average signal attenuation over bare tree signal attenuation.

L-band measurements made by Vogel and Goldhirsh over 600 km of 2-lane and 4-lane highways and rural roads in Maryland using helicopter platforms and the MARECS-B2 satellite were used to derive an empirical "best fit" expression of cumulative fade distribution [17]. Data was taken at elevation angles of 210, 300 45° and 60° and signal arrival was primarily perpendicular to the roadway, corresponding 10 maximum shadowing conditions. The dominant sources of shadowing were the roadside tree canopies with some shadowing from utility poles and only minor multipath. Roadside trees were primarily deciduous and resulted in 55% to 75% shading of the right lane io the direction of (ravel. Figure 1 from [17] plots some results of the cumulative fade model. Model agreement with the empirical distributions is within 1 dB for all four elevation angles measured.

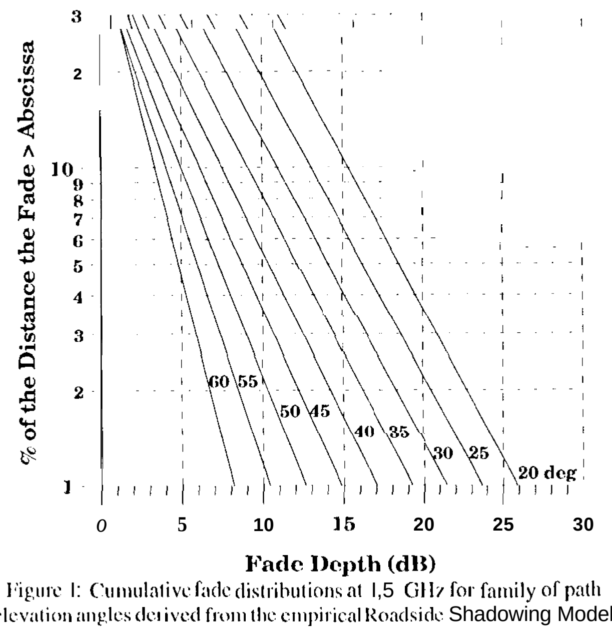

Figure 1: Cumulative fade distributions at 1,5 GHz for family of path elevation angles derived from the empirical Roadside Shadowing Model by Goldhirsh and Vogel [17].

Note the strong dependence of fading statistics on elevation angle. Combine these with figure 2 showing the elevation angle contours over North America resulting from a direct broadcast satellite favorably located at 100° west Longitude. Assuming similar ground environments, a user in rural Texas might see a 10 dB signal fade less than ?% of the time while a user in Washington state would experience a 10 dB fade 20% of the time. Similarly, if we choose a fixed fading percentage of 2%, the user in Texas requires only a 10 dB margin while the user in Washington state requires an 18 dB margin. One solution to this problem is to taper the satellite beam gain to direct more power toward regions with at elevation angles. Iridium satellite design uses this approach to provide 8 dB more gain to users at an elevation angle of 10° than users at an elevation angle of 50° [21]. Gaudenzi and Giannetti [25], emphasizing the (imitability of high elevation angles, propose a constellation of satellites in Molniya type highly elliptical orbit (HEO) after a detailed orbit tradeoff study clone by British Aerospace, et al. [26]. The proposed HEO constellation would provide the majority of Europe with a elevation angle greater than 60°.

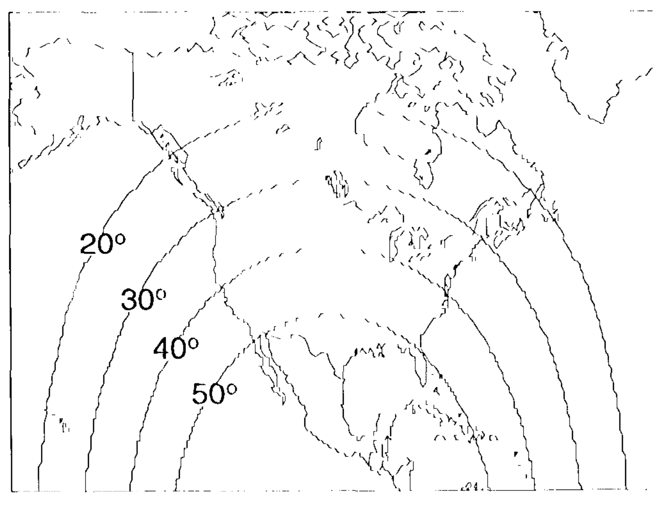

Figure 2: Elevation Angle Contours for direct broadcast GEO-stationary satellite favorably located at 100° west Longitude for North American Service.

While cumulative fade statistics are important they do not provide sufficient information to design fading counter measures. Additionally we need some measure of fade and non-fade durations. These depend on both the fading environment and the mobile speed through that environment. We should also consider signal phase fluctuation statistics to complete the picture.

Signal Margin and Time Diversity as Satellite Mobile Fade Mitigation Techniques

With the mobile environment comes rapidly time varying signal fading but also the possibility of combating the same with temporal diversity techniques. The effect of the LMSS shadowing environment is to knock out blocks of bits, block size varying with the fade duration. Time diversity techniques can be used to randomize the outage patterns through interleaving or repeat transmission so that some form of channel coding can reconstruct the original data in the decoding process. In the case of interleaving, block or convolutional error correcting codes are often applied before interleaving and the effectiveness of the decoding procedure in reducing bit error rate depends not only on the average blocking percentage but on the ability of the deinterleaver to randomize the fading events chopping up long fades into smaller portions and redistributing them so that the error correcting code can handle them. In fact if a time diversity technique is unable to randomize a fading event (interleaving) or produce uncorrelated faded samples of the same symbol (repeat transmission) no reasonable channel coding technique will be capable of providing significant BER improvement on data sent over the LMSS channel. How does one predict the effectiveness of time diversity techniques and compare their effectiveness with other techniques such as simple addition of signal fading margin. This question will be addressed in this section by investigating an example time diversity strategy, i.e. repeat transmission.

The combination of fade and non-fade duration statistics are commonly used to characterize the temporal nature of signal fading in the mobile channel. In our investigations of repeat transmission we processed the signal level time history generating the related statistics, joint signal fading and fade autocorrelation, which more succinctly predict the effectiveness of a simple dual transmission scheme. We first generate the statistic $P_2(\tau,Z)$, the joint probability of fade at time (t) and $(t+\tau)$:

$$P_2(\tau,Z) = p(S(t) < -Z\ dB, S(t+\tau) < -Z\ dB) \qquad (1)$$

where Z is the allowable fade margin and S(t) is the signal power time history normalized to the unobstructed line-of-sight signal power. If we define the hard limit inverting function H(x) as

$$H(x) = \begin{cases} 1\ ;\ S(t) < -Z\ dB \\ 0\ ;\ S(t) >= -Z\ dB \end{cases} \qquad (2)$$

Then

$$E[H(S(t))H(S(t+\tau))] = p(S(t) < -Z\ dB, S(t+\tau) < -Z\ dB) = P_2(\tau,Z) \qquad (3)$$

is the signal blocking percentage for single transmission diversity given a fade margin of Z dB.

Note that $P_2(0,Z) = p(S(t) < -Z\ dB) = P_1(Z)$, (4)

Also note that fade autocorrelation, as we have defined it is:

$$R(\tau, Z) = \frac{P_2(\tau, Z)}{P_1(Z)} \qquad (5)$$

Vogel and Torrence recently completed S-band mobile propagation measurements in and around NASA JPL [20]. The TDRSS satellite transmitted a 2050" MHz carrier only signal that allowed for 35 dB of measurable fading relative to the line-of-sight signal strength. Elevation angle to the S/C was 22°. The test course included several types of terrain, NASA JPL (12 minutes), Six Lane Freeway (6 minutes), Downtown Pasadena California (7 minutes) and Residential (20 minutes). Figure 3a shows the joint fading statistic $P_2(\tau,Z)$ averaged over the entire 45 minute run and parameterized on the allowed fade margin Z.

At a time offset equal to zero, the y-axis value is the overall sample probability, $P_1(Z)$, that the signal fade exceeds the fade margin. Assuming we have collected a sample of signal fade statistics corresponding to typical mobile conditions, we now have a set of curves that at once indicate overall fade statistics and that decompose and display relative effectiveness of fade margin and time diversity in reducing the fraction of signal loss due to fading. For example, increasing the fade margin from 4 to 7 dB reduces fade time fraction from 241% down to 18%. A time diversity technique, such as retransmission, with a time delay of 0.6 seconds achieves the same effect. The sharp drop off of the joint fade statistic for short delays indicates that a significant amount of fading is short duration interspersed with non-faded times and can be mitigated with short delay retransmission or a combination of interleaving and coding

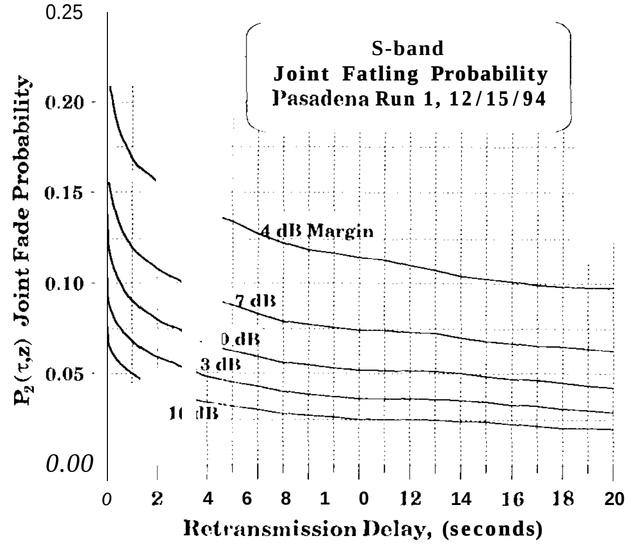

Figure 3a: Probability that Both Transmissions are Blocked; Statistic Averaged Over 45 minute Run through Various Terrains

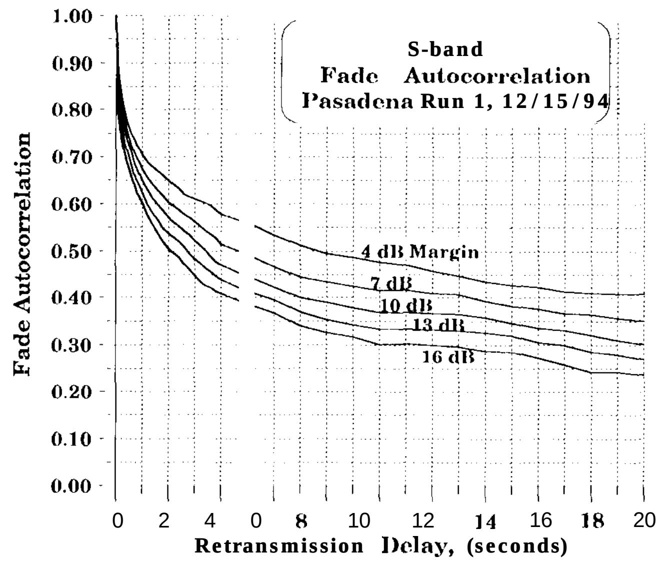

Figure 3b: Autocorrelation of Signal Outage Events; Statistic Averaged over 45 minute Run through Various Terrains

Figure 3b is similar to figure 3a except all curves have been normalized to a value of 1.0 at a time offset of zero. The result is the conditional probability of experiencing a signal outage τ seconds in the future given that you are presently in the faded state, i.e. a true autocorrelation of the outage events. The curves show the increasing value of retransmission time diversity as the fade margin increases. This is expected since higher fade margins eliminate many lower level fades opening up wide spaces of non-fade times that can be effectively utilized by time diversity techniques.

The results shown in 3a and 3b suggest combinations and trade-offs of fade margin and retransmission time delay that achieve some desired signal outage probability. In this capacity they are a tool to assist in communications system design.

We can extend this by parameterizing our analysis by terrain. Figure 4a shows the joint fading statistic $P_2(\tau,Z)$ as a function of terrain type for a fade margin of 10 dB. The Linda Vista residential roadway was lined with a canopy of leafless deciduous trees on both sides of the street presenting a roughly 60% tree shadowed environment. Note that the 33% fraction of time faded agrees well with the 30% value predicted from figure 1. Figure 4b, fade autocorrelation, shows how time diversity is more effective for some terrain types. Even though Linda Vista had twice the overall fading rate of Downtown Pasadena, a time diversity of less than 2.0 seconds is twice as effective at Linda Vista because the tree shadowing is characterized by many short duration outages while city driving results in longer periods of blockage due to larger blocking structures and slower mobile speeds. Not unexpectedly, time diversity is very effective in the freeway environment as higher mobile speeds result in shorter blockage times and the over all signal blocking percentage is lower.

This type of analysis can be extended to other time diversity schemes such as combined interleaving and coding, or multiple retransmissions. It could also be extended to antenna diversity.

Other Diversity Techniques For the Satellite Only DBS Radio Transmissions

As mentioned earlier, LMSS outdoor propagation effects are dominated by signal shadowing for the first 15 1020 dB of fading. This limits the applicability of various diversity schemes. Frequency diversity or spread spectrum techniques are not effective because the shadowing effects are relatively flat across reasonable operating frequencies. Polarization diversity is limited because the shadowing can significantly diminish the polarization isolation. Measurements of tree shadowed signals reported in [18] showed cross-polarization levels 15-20 dB below co-polarization levels indicating that polarization isolation techniques have only marginal value.

Spatial antenna diversity is a scheme that can be effective for short distance outages such as those caused by tree branches. Consider a scenario of two spaced antennas atop a vehicle where each antenna feeds a separate receiver. If signal levels at the two antennas are even partially uncorrelated, selection of the higher level signal will result in some performance improvement. In fact if vehicle speed is recorded as part of a propagation test record, one can easily convert the fade vs. time data to fade vs. distance data and generate antenna diversity performance curves similar to figures 3a, 3b, 4a and 4b. As an example, the Linda Vista run of figures 4a and 4b included only one stop with average speed of about 12 meters/sec. Thus an antenna separation of 2 meters would be roughly equivalent to retransmission with a time diversity of 0.17 seconds. Based on the fade vs. time data such a two antenna diversity scheme would result in a 20% reduction in the time spent faded more than 10 dB. As vehicle speed decreases, time diversity becomes less effective whereas antenna spatial diversity maintains the same average performance

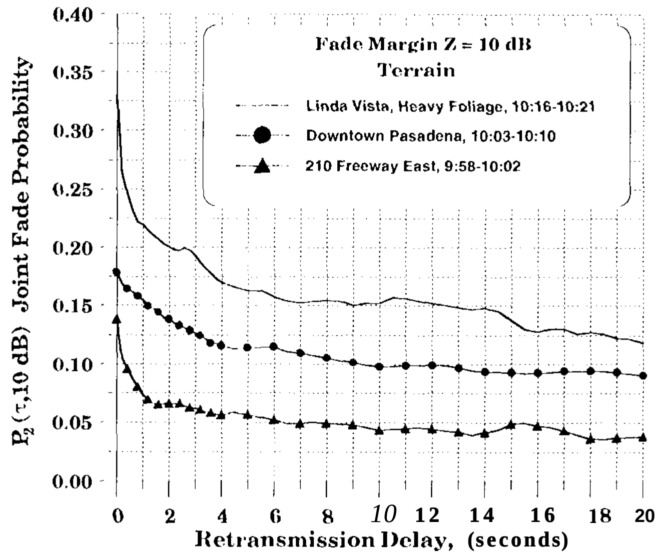

Figure 4a: Probability that Both Transmissions are Faded by More Than 10 dB; Parameterized by Terrain Type

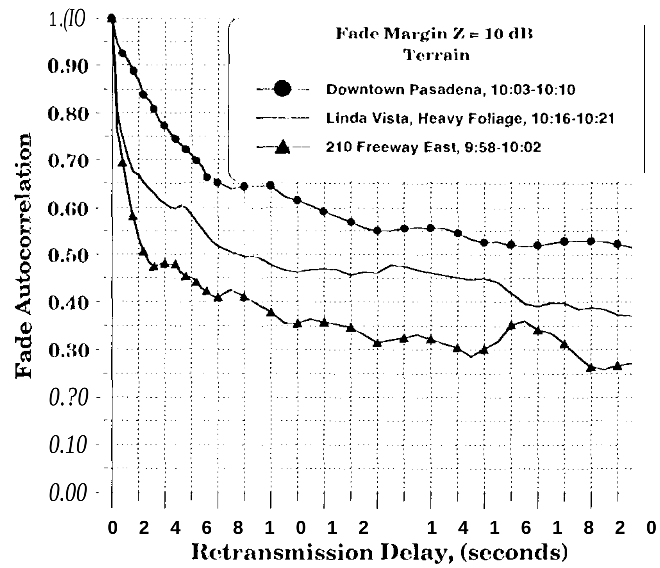

Figure 4b: Autocorrelation of Signal Outage Events; Parameterized by Terrain Type

enhancement regardless of vehicle speed.

Received Signal Phase Fluctuations

In brief, Vogel and Goldhirsh analyzed signal phase fluctuations recorded in "extreme" rural-suburban propagation environments, i.e., measurements made along roads having a "continuum of overhanging tree canopies where almost persistent shadowing occurred." They found that even in this worst case that for 98% of the time, measured phase fluctuation was no worse than +/-20° over a fading range of 2 to 8 dB. Based on this and results from more benign channels, they concluded that, "the influence of phase fluctuations on demodulation techniques at the elevation angle considered, (e.g. 51°), is minimal and that the LMSS channel characteristics can be estimated without considering phase." Recalling that multipath components were observed to be 15-20 dB below the line-of-sight signal level we may additionally conclude that phase fluctuations in the rural and suburban environment will not be significant except during deep fades. Conditions will worsen for lower elevation angles where deep fades and multipath arc more prevalent. A recent paper by Goldhirsh and Vogel investigates 1-band amplitude and phase fluctuations for Satellite transmission scenarios at elevation angles ranging form 7°1014° [28]

DBS-Radio Urban Propagation

Effectiveness of lime diversity in all environments diminishes as the mobile speed decreases. When mobile speed is reduced to zero, i.e. stationary, time dive.rsity is totally ineffective. This is particularly a problem in the city environment where traffic is stop and go and structures may completely block the line-of-sighl signal. The ATS-6 satellite was used by Hess to measure UHF and L-band excess path losses in various cities [11]. As an example, in Denver, the satellite appeared to the southwest at 32° elevation. Streets running parallel 10 the satellite direction, i.e. NE/SW, experienced fades greater than 6 dB only 10% of the time, whereas streets running perpendicular experienced fades greater than 29 dB 10% of the time. This latter condition exceeds the mitigation capacity of any reasonable combination of fade margin and time diversity.

Urban Land-Based Gap Fillers

1 mcl-based signal boosters have been suggested for this difficult urban environment. '1'0 minimize the spectrum requirements, we can further require the boosters to transmit the same program and signal structure as the satellite. The goal is to fill in the coverage gaps in the heavily shadowed city area. An unavoidable result of this scheme is the creation of severe multipath and intersymbol interference, ISI. Consider a DBS signal channel coded to a rate of 300,000 synltmls/see, (sps). One symbol time is equivalent to only 3.0 kilometers at the speed of light. Thus multiple symbol delays between booster signals arc likely and the result will be IS I. Add to this the fact that low elevation angle mobi le transmissions arrive at the mobile scattered by many intervening obstacles and you have at the receiver a combination of lime delayed Rayleigh faded copies of the desired signal. Mutipath can be n desirable phenomena if wc consider that it is equivalent to the repetitive transmission of the same signal, The signal from each source travels a different path to the receiver and thus experiences independent fading. This path diversity can be utilized i f the modulat ion scheme is sophisticated, such as spread spectrum, or if the receiver has the sophistication 10 deconvolve the channel 1S1 effects, [22]. in further analysis wc can consider the satellite as onc of the boosters or if booster signal strength is overwhelming wc can equivalently ignore the satellite signal,

Adaptive Equalization

Consider a single channel pcr carrier QPSK satellite system with on channel boosters in a metropolitan area. The requirement here is for an adaptive equalizer that can follow the phase and amplitude variations of the Rayleigh signal envelopes and deconvolve the combination of delayed signals were even the relative delays vary as the booster 10 mobile geometry changes.

This type of environment was investigated via computer simulation, Three Rayleigh faded copies of a QPSK 300,000 sps data stream arc combined, Each signal is offset from the next by onc symbol time delay and the average power of each component is equal, The Doppler spread of +/- 213 Hz on each signal is equivalent 10 n vehicle speed of IO() km/hr given a 2.3 GHz S-band transmission frequency. Signals plus while Gaussian noise (WGN) were applied to a Lattice Predictive Decision Feedback Equalizer, (Lattice PDFE) after Ling and Qureshi [23] and tbc resulting uncoded bit err or rate was measured as a function of combined signal to noise ratio. Figure 5 shows the results for several different configur at ions, As part of JPL's DBS receiver development, we have used a Constraint Length =7, Rate = 1/2 convolutional code in conjunction with interleaving and a (160,140) Reed-Solomon code to combat short signal outages. An uncoded bit error rate, (BER), of 10^{-2} is nccdcd to achieve 10^{-6} BER on such a concatenated coded channel assuming soft decision Viterbi decoding of the convolutional code. BER and Bit SNR values refer to information bits, i.e. results include the SNR cost of equalizer training symbol overhead.

The top curve indicates that the 1S1 and Rayleigh fading completely obliterate the normal QPSK signal structure with no chance of data recovery without equalization. The second curve shows the performance of a single diversity channel with onc out of five symbols used for equalizer training/tracking. The third curve down is performance of the same equalizer structure but with one out of three symbols used for training, A bit SNR of 19 dB is reasonable in a ground transmission environment and thus our concatenated code performance of 10^{-6} is achievable.

The fourth curve displays the performance of a dual selection diversity system, where each receive string has a Lattice PDFE and the equalizer outputs are selected based on estimates of equalizer tracking error that are normally performed and available as part of the equalization process. The diver'sily gain is about 7 dB at the desired operating point. 'This is noteworthy for the DBS-Radio system designer.

The fifth curve down assumes a Rician channel where the unfaded signal, bas a power equal 10 the average sum power of the two Rayleigh components. Diversity = 1 is also assumed, Note the improved equalizer performance for this Rician channel as compared to the Rayleigh channel even though both channels produce a 50% error rate without equalization.

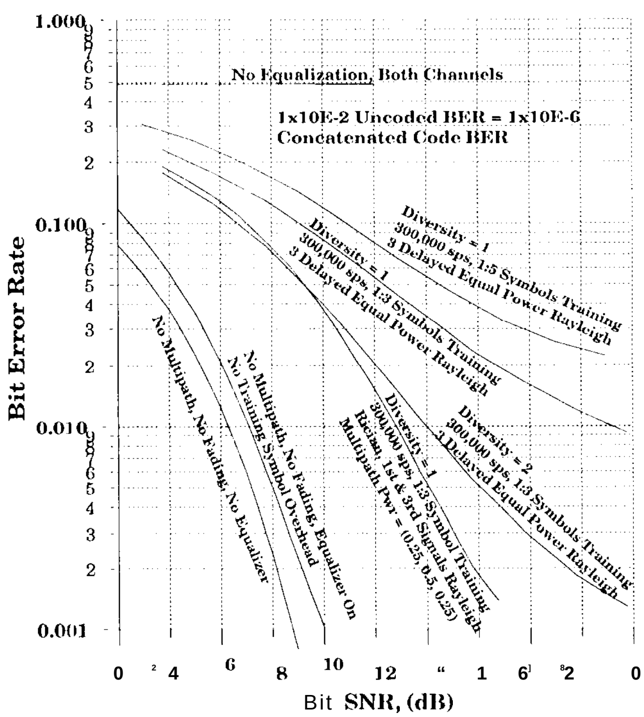

Figure 5: Lattice Predictive Decision Feed Back Equalizer Performance in Rayleigh and Rician Fading. Max. Doppler = 213117, Equivalent Vehicle Speed = 100 km/h at S-band 2.3 GHz. Bit SNR Corrected for Training Symbol Overhead.

The sixth curve down shows performance of the Lattice PDFE in a white Gaussian noise only channel. Finally **the standard** theoretical performance 01 QPSK in a WGN channel is given as the last curve, The **1** dB performance penalty cm the WGN channel is a consequence of adaptive equalizer attempts to track phantom channel variations caused by Gaussian noise.

Many different equalizer structures arc possible but all at the expense of *increased* receiver complexity. The lattice PDFE was chosen because of it's adaptive ability, it's robustness to round-off errors and regular structure which lend it to VLSI implementation and its reduced computational complexity relative to other schemes. A more thorough description of the combined receiver-equalizer performance in the booster aided DBS environment is presented in another paper in this conference [29].

Coded Orthogonal Frequency Division Multiplex, (COFDM)

Coded Orthogonal Frequency Division Multiplex, (COFDM), is a technique useful in mitigation of frequency selective multipath fading and it is the basis of the Eureka 14.7 digital audio broadcast, (DAB), standard. The technique is particularly applicable to the on-frequency repeater transmission scheme. Onc or more high raft compressed and *channel coded digital audio* programs are transformed into N interleaved lmv-rate sub-streams and modulated onto separate subcarriers equally spaced 1 /N'f 1 lz, where '1' is the symbol timing. The number of carriers is chosen so that fading is flat across a single carrier but fading is independent among adjacent bits that have been assigned to diverse carriers and thus frequency interleaved. The 'channel' effect on any particular carrier *reduces to an amplitude scaling* and a phase rotation. The usc of a PSK signaling format then eliminates the need for amplitude tort-cc(irm and differential phase encoding at the transmitter allows differential phase correction at the receiver.

As with equalization techniques, COFDM diversity gains presume frequency selective fading across the signaling bandwidth. in rural and suburban environments and in the satellite broadcast environment the delay spread of the channel may be so short that fading tends to be flat or dependent across the channel. Typically the delay spread needs to be greater than the reciprocal of the program carrier spacing. When COFDM is working, subcarriers found in a spectral null will produce symbol errors at the detection stage, but these symbol errors arc interleaved with correctly detected symbols from non-faded subcarriers and the channel coding scheme can effectively recover the lost in formation.

In an well written paper [27], Sari et al, show that OFDM is functionally equivalent to a single channel pcr carrier system employing frequency domain equalization. They further show that the two techniques with channel coding have essentially the same performance results in a frequency selective channel but that the single channel pcr carrier scheme has the advantage of low sensitivity to non-linear distortion, such as that found in a satellite transponder. The single carrier approach also alleviates the carrier synchronization problems associated with 01 'DM.

Antenna Directivity

This technique al once combats four propagation impairments. First, antenna directivity provides gain relative to an omni-directional antenna and can thus selectively enhance a desired signal and mitigate attenuation on that signal caused by shadowing. Second, antenna directivity reduces the number of multipath components by discriminating against much of the possible range of signal azimuth arrival angle. '1'bird and forth, this same multipath discriminat ion also decreases Delay Spread and Doppler Spread in the booster assisted mobile environment where multipath signals with maximum delay and maximum Doppler offset often arrive at the mobile from nearly opposite directions [19]. If a sectored antenna is used with multiple receivers, (diversity), the effect is to flatten the channel response as seen by any rmc receiver. The challenge of this technique is to find a way to rapidly switch antenna gain pointing or antenna sector selection toward the best signal direction as it varies with receiver motion through the multipath environment. Yamao and Nagao [24] propose a predictive antenna selection scheme that could be combined with a azimuth sectored antenna such as the one described by Murata c1 al in [19]. Antenna directivity also combats co-channel interference and can be combined with antenna diversity.

Spread Spectrum

Spread Spectrum techniques employ a form of frequency diversity to combat fading in a frequency selective channel. As an example, Gaudenzi and Giannetti [25] describe a candidate direct-sequence spreading scheme for usc in a combined satellite - ground based single frequency network. The PN sequence self-noise that typically limits the capacity of a CDMA system is overcome by appropriate phasing of Gold code spreading sequences. Code synchronization is possible because radio *programs* using *different* Gold codes arc all transmitted together from the same silts. A Rake receiver structure is used to combine the three delayed signals with the largest signal powers, this includes both the satellite and booster signals. The system approach allows for data rate flexibility and distributed uplink. Finally VLSI CDMA receiver technology has been demonstrated by Qualcomm in their two-way digital radio design.

Summary

To properly design a DBS-Radio system it is imperative to understand the associated propagation impairments, their source, their nature and their extent. Wc have summarized these propagation effects in three generic environments, indoor, rural - suburban mobile, and *urban mobile and in* each case suggested several techniques to mitigate these effects. In addition, the references provide a wealth of more detailed information useful to the DBS-Radio system designer.

	Satellite/Sirlltllatcrl Satellite Propagation Tests	)ther indoor Radio Prop. Tests
Basic Test Conditions		
Frequency	[2,3] 0.7 -1.8 GHz [4] (),9,).6, 26 Gil/	).5 10 3.0 GHz
Elevation Angle to Xmitter	[2,3] 12" to 45° [4] 36° to 55"	0°
Spatial Signal Variations	Signal Loss	ignal Loss
Non-Metallic Residential	Mean = 5 - I I [it{, [2,3] hlcan=610 8 dB, Std Dev = 2-3 dB [4]	
Some-Metallic Office	Mean = 5-14 dB, Std Dev = 2-10 (ill [2,3]	Mean = 10-15 dB, Std Dev = 3-6 dB [6] Mean Signal Attn. decreases by 1.5-2.0 dB per loor as one goes up in a multi-story building 7,8]
Null Spacing Non-Metallic Residential Some-Metallic office	2-4 λ [2,3];	).5 -1.5 λ, [6]
Cause	Standing Wave Pattern, Possibly, the higher elevation angle produces the different pattern.	Standing Wave Pattern
Frequency Variations		
Large Scale Non- and Some-Metallic Structure	2-S dB attn. increase per octave [?,3] 2-3 dB attn. increase per octave [4]	
Office Buildings and Metallic	2-3 (ill attn. decrease per octave [?]	I-3 dB attn. decrease pcr octave [7] 2-3 dB attn. decrease per octave [9]
Cause	Main Signal Penetration and Propagation Through walls and ceilings, favors 10WCI frequencies.	Main Building Signal Penetration and propagation through openings, favors higher frequencies.
Small Scale	2-10 dB Signal Troughs 5-30 MHz Wide[3]	
Cause	Variations in Standing Wave Pattern with Frequency	
Temporal Variations	<0.5 dB unless antenna line-of-si~,hl blocked by person, which causes ldes of 6-10 dB. [3]	4 Hz BW, Rician K = -610-12 dB; Dynamic Range = 1 7-30 dB due to movement of people and doors inside and outside traffic. [6]
Cause	Main propagation through walls and ceilings and higher elevation angle signal encounters fewer moving reflectors and refractors	Main Propagation Probably through openings and Low Elevation angle. Result is standing wave pattern changes with changing pattern of
Delay Spread Non-Metallic Single Story Office Buildings and Metallic	≈1 () -30 ns Total, [3] ≈ 1 00 ns Total, [3]	Rooms: ≈ 200 ns Total, ≈50 ns RMS Hallways ≈ 350 Hallways; [5] 1 .5 GHz
Difficult Structures		
Non-residential buildings	Loss: Mean = 20 dB, Std. 10 dB	---
Buildings shadowed by trees, other buildings or mountains	12-15 dB Excess Loss due to Trees in Satellite Signal Path [4]	
Buildings with significant metal in construction elements	Metal Shack: Mean Loss = 9-1 1dB; Mobile Home: Mean Loss = 20+ dB [3] 15-22 dB for houses with aluminum backed sheetrock; 24+ dB for mobile homes [4]	Metal Covered Roof, Walls and Mesh Screen on Windows and Doors. Median Attenuation = 26-32 dB, Rayleigh Distributed [10]

Table 1- Summary of Reviewed Indoor Propagation Test Results that Apply)BS-R

	Rural and Suburban Satellite Mobile Fading
Basic Test Conditions	
Frequency	0.87 & 1.5 GHz, Some 2.6 GHz [17]; 1.6 & 2.5 GHz [18]
Elevation Angle to Xmitter	≥15°
Fixed Sift Tree Attenuation 1 or 2 Trees, Roadside	Si nal J .0,s.s Typical = 4-9 dB, Std Dev = 3-7 dB [18] Bare Trees = 5-14 tilt, for Elev 40'-150' ΔFade = 0.35 dB/°Elev, UHF 870 MHz [17] Full Foliage .7-19 dB, for Elev 40"'-150' ΔFade = 0.48 dB/°Elev, UHF 870 MHz [17] Foliage Factor: Mean Fade Full Foliage (cl}]): 1.35 x Mean Fade Bare Tree (dB)[17] UHF Fade = 1.3 dB/Meter of Canopy, L-Band Fade = 1.8 dB/Meter of Canopy [17] After 15-20 dB of Direct Signal Fade, Rayleigh multipath begins to dominate. Cross-Polarization signal level is 15-20 below Co-Polar Level. [18]
Spatial Auto Correlation S - L Fade Level Cross Correlation L-Band Fade Level Auto Correlation S-Band Fade Level Auto Correlation	 None Observed [18] Near 0 at lag of 10 λ [18]; Near 0 at lag of 1-2 meter @ 5-10 λ [17] Near Oatlag of 20-30 λ [18]
Mobile - Spatial Variations **Source Perpendicular to Road** Cumulative Fade Stats vs Elevation Angle	 **Main Signal Impairment is Tree Shadowing** See Figure 1 Tree Scattered Multipath Signals are 15-20 below the main signal so when main signal is faded by this amount the received signal becomes Rayleigh in nature. [18]
Source Parallel to Road Open Rural kind,.. No Trees Canyon Roads in Colorado	**Main Signal Impairment is Mutipath Fading** L-hand, dB.5. No Elevation Dependence between 30° and 600 [17] L-band, 2-8 dB... At Elevation Angle of 30° [18]
Frequency Variations Freq Scaling	 Same Mean Fade Level at L and S hand [18] [17], Observed Over UHF, L-band & S-hand
Polarization Effects	Cross Polarized Signal averaged 15-20 dB below Co-Polarized Signal Level [18] Unfortunately, Polarization Diversity degrades rapidly with increasing fade level e.g. at 5 dB fade level, polarization isolation is down to only 11 dB. [17]

Table 2 - Summary of Reviewed Rural and Suburban Propagation Test Results that Apply to DBS-R

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